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14. ABSTRACT

We have performed a series of theoretical and experimental research projects to support the development of coherent-feedback quantum control and to stimulate interest in the subject from a wider research community. Coherent-feedback quantum control is a qualitatively new branch of control engineering with direct relevance to nanoscale and quantum technologies, which draws heavily upon the novel modeling framework of quantum stochastic differential equations. Our main goals in this work have been to establish the practical utility of such

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a. REPORT	b. ABSTRACT	c. THIS PAGE			Hideo Mabuchi
UU	UU	UU	UU		19b. TELEPHONE NUMBER 650-723-0201

Report Title

Coherent-feedback quantum control with cold atomic spins

ABSTRACT

We have performed a series of theoretical and experimental research projects to support the development of coherent-feedback quantum control and to stimulate interest in the subject from a wider research community. Coherent-feedback quantum control is a qualitatively new branch of control engineering with direct relevance to nanoscale and quantum technologies, which draws heavily upon the novel modeling framework of quantum stochastic differential equations. Our main goals in this work have been to establish the practical utility of such new control and analysis techniques in atomic and optical physics applications, to understand what degradation (if any) should be expected in the real-world performance of coherent-feedback quantum control schemes that are derived using idealized models, and to begin to connect known, intuitive coherent feedback schemes to formal synthesis methods from optimal control theory.

Enter List of papers submitted or published that acknowledge ARO support from the start of the project to the date of this printing. List the papers, including journal references, in the following categories:

(a) Papers published in peer-reviewed journals (N/A for none)

Received		Paper
2012/08/27 1(	3	Hideo Mabuchi. Coherent-feedback control strategy to suppress spontaneous switching in ultralow power optical bistability, Applied Physics Letters, (05 2011): 193109. doi: 10.1063/1.3589994
2011/10/02 1'	1	J Kerckhoff, D S Pavlichin, H Chalabi, H Mabuchi. Design of nanophotonic circuits for autonomous subsystem quantum error correction, New Journal of Physics, (05 2011): 55022. doi: 10.1088/1367-2630/13/5/055022

TOTAL: **2**

Number of Papers published in peer-reviewed journals:

(b) Papers published in non-peer-reviewed journals (N/A for none)

Received	Paper

TOTAL:

Number of Papers published in non peer-reviewed journals:

(c) Presentations

H. Mabuchi, "Photonic circuits for coherent-feedback quantum control," OPTO San Francisco, January 27, 2011
H. Mabuchi, "Quantum feedback," series of six lectures at Ecole de Physique des Houches, July 2011
H. Mabuchi, "Principles and Applications of Coherent Feedback Control," GRC on Physics Research and Education, Mt. Holyoke College, August 2011
H. Mabuchi, "Design and analysis of autonomous quantum memories based on coherent feedback control," 3rd International Conference on Quantum Error Correction, USC, December 2011
H. Mabuchi, "Quantum-coherent feedback in photonic circuits," Royal Society Theo Murphey Meeting on Principles of Quantum Control Engineering, Chicheley, UK, December 2011

Number of Presentations: 5.00

Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received	Paper

TOTAL:

Number of Non Peer-Reviewed Conference Proceeding publications (other than abstracts):

Peer-Reviewed Conference Proceeding publications (other than abstracts):

Received Paper

TOTAL:

Number of Peer-Reviewed Conference Proceeding publications (other than abstracts):

(d) Manuscripts

Received Paper

TOTAL:

Number of Manuscripts:

Books

Received Paper

TOTAL:

Patents Submitted

Patents Awarded

Awards

Graduate Students

NAME	PERCENT_SUPPORTED	Discipline
Yeong Dae Kwon	0.22	
Joseph Kerckhoff	0.14	
Orion Crisafulli	0.64	
Crystal Bray	0.01	
Benjamin Haynor	0.04	
Anthony Miller	0.04	
Gopal Sarma	0.08	
Jie Wu	0.18	
FTE Equivalent:	**1.35**	
Total Number:	**8**	

Names of Post Doctorates

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Names of Faculty Supported

NAME	PERCENT_SUPPORTED	National Academy Member
Hideo Mabuchi	0.03	No
FTE Equivalent:	**0.03**	
Total Number:	**1**	

Names of Under Graduate students supported

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Student Metrics

This section only applies to graduating undergraduates supported by this agreement in this reporting period

The number of undergraduates funded by this agreement who graduated during this period: 0.00

The number of undergraduates funded by this agreement who graduated during this period with a degree in science, mathematics, engineering, or technology fields:...... 0.00

The number of undergraduates funded by your agreement who graduated during this period and will continue to pursue a graduate or Ph.D. degree in science, mathematics, engineering, or technology fields:...... 0.00

Number of graduating undergraduates who achieved a 3.5 GPA to 4.0 (4.0 max scale): 0.00

Number of graduating undergraduates funded by a DoD funded Center of Excellence grant for Education, Research and Engineering: 0.00

The number of undergraduates funded by your agreement who graduated during this period and intend to work for the Department of Defense 0.00

The number of undergraduates funded by your agreement who graduated during this period and will receive scholarships or fellowships for further studies in science, mathematics, engineering or technology fields: 0.00

Names of Personnel receiving masters degrees

NAME
Total Number:

Names of personnel receiving PHDs

NAME	
Joseph Kerckhoff	
Anthony Miller	
Total Number:	**2**

Names of other research staff

NAME	PERCENT_SUPPORTED
FTE Equivalent:	
Total Number:	

Sub Contractors (DD882)

Inventions (DD882)

Scientific Progress

During our ARO-sponsored project we have contributed to both the experimental and theoretical progress of coherent-feedback quantum control. On the theoretical side it took us much longer than expected to understand how some of our basic intuitions regarding atomic physics models would manifest in the framework of quantum stochastic differential equations, and that limited our initial rate of progress. We eventually however became quite comfortable in applying the new modeling framework to a wide range of experimentally realistic models however and have performed detailed analyses of potential applications of coherent feedback control in quantum engineering and photonics. On the experimental side we were surprised by the discovery that small variations of tensor coupling effects across a laser probe beam can cause severe decoherence to the collective atomic spin state, and dealing with this problem prevented us from immediately moving on to work on adding the coherent feedback beam path. In analyzing this effect however we learned some important new things about decoherence mechanisms in polarization spectroscopy with real multi-level atoms, and we also succeeded in demonstrating a new method for suppressing these deleterious effects (dual-wavelength polarization spectroscopy), ultimately reaching the spin projection noise limit for coherent readout of collective spin in a cold atom ensemble. We have likewise experimentally implemented a selection of key building blocks for synthesizing optimal coherent-feedback controllers in the coherent-Linear Quadratic Gaussian setting, and succeeded in initial demonstrations of basic principles of coherent-feedback control of quantum oscillators.

Specific accomplishments during the award period include:

• We have successfully applied some recent abstract theorems from the theory of quantum stochastic differential equations to concrete atomic physics models of widespread interest for quantum engineering; as a result we have been able to provide the first compelling examples of the practical utility of these theorems.

• We have designed and built specialized optical parametric amplifiers for use in quantum optics experiments to test fundamental principles of coherent-feedback quantum control.

• We have developed a new experimental technique for compensation of tensor coupling effects in polarization spectroscopy of dense Cesium clouds, based on dual-wavelength probing with carefully matched spatial profiles, and utilized it in experiments reaching the spin shot-noise limit for atomic magnetometry.

• We have developed a new code base of Mathematica scripts for manipulation of linear quantum stochastic differential equation models and for Linear-Quadratic-Gaussian optimization of coherent feedback controllers for linear quantum stochastic models. We have used these new tools to discover models in which quantum-coherent feedback can outperform classical feedback control by much larger factors than previously known.

Our theoretical work on the concatenation and approximation of Quantum
Stochastic Differential Equation (QSDE) models culminated in a New Journal of Physics paper on coherent feedback control in a nanophotonic setting. The new scheme is a coherent-feedback implementation of the Bacon-Shor subsystem code; it has received significant attention and was chosen for the "IOP Select" feature of the New Journal of Physics. The design and analysis of this quantum memory relied heavily on our previous theoretical studies of adiabatic elimination in quantum stochastic differential equation (QSDE) models. We have recently also managed to perform an analysis of the role of propagation losses in this type of coherent-feedback quantum circuit, which has required the development of a new computer algebra approach to QSDE concatenation and adiabatic elimination based on term-rewriting. Beyond the end of our ARO award we plan to extend the propagation loss analysis to the Bacon-Shor subsystem code and are also exploring a generalization of the computer algebra framework that may be suitable for public distribution. In the work leading up to this publication we successfully applied the QSDE limit theorem developed previously in our group to reduce ab initio quantum input-output models based on the Jaynes-Cummings model to simple scattering matrix descriptions that could be concatenated to yield circuit models of manageable complexity. Our results demonstrated the use of this important new QSDE analysis technique for the first time in a concrete setting of broad interest. We found that the closed-loop master equation that we derived for the coherent feedback system was straightforward to interpret and exhibited interesting robustness properties with regard to disturbances that might act on the controller (as opposed to the plant).

The second focus of our theoretical work has been coherent linear quadratic gaussian (CLQG) control optimization. We have worked to try to understand in conceptual terms the performance gap between classical and quantum LQG, whose existence was established in prior numerical work by Nurdin, James and Petersen. We have incorporated CLQG optimization within the term-rewriting framework
mentioned above, and have managed to improve upon the performance gap originally discovered by Nurdin and co-workers. We have recently managed to understand this gap in an intuitive way and we believe that this advance will enable further future breakthroughs in understanding how coherent feedback control can be applied optimally in nonlinear settings such as quantum decoherence suppression. We have also worked to connect these theoretical results to our ongoing experiment in CLQG control by finding an example of an LQG scenario with a provable quantum-classical performance gap, which we should be able to
implement in the laboratory using realistic experimental parameters. As part of this effort we have completed a preliminary analysis of what measurements must be made in order to verify CLQG performance, assuming a restriction to homodyne and heterodyne-type photo-detection schemes.

Our experimental work continues to involve two related projects. The first centers on the use of optical amplifiers for use in coherent feedback loops. Although during the award period we began to investigate optical materials for the construction of parametric amplifiers at 852nm or 894nm, our laboratory characterizations led us to conclude that commercial materials are not yet of sufficient quality to provide the high gain and low loss that we require. We therefore switched to a 1064nm setting and quickly assembled the necessary components to construct not only a waveguide-PPLN parametric amplifier but also a complete "general open oscillator," which has been proposed in the theoretical literature as a universal building block for controller synthesis in the linear setting of coherent-feedback quantum control. As of the end of the ARO award period we have not yet completed a first round of publication-worthy measurements with this system, but expect to do so within the next year.

The second experimental project involves tensor interactions in Faraday spectroscopy of the collective hyperfine spin state of cold Cesium atoms. Building on prior theory and simulation results on potential mechanisms for canceling tensor effects via dual-wavelength (852nm and 894nm) probing, we performed a successful initial experimental demonstration of the cancellation scheme and integrated this new technique in the experimental setup for coherent-feedback probing of the cold atomic spins. We successfully demonstrated a dual-wavelength probing technique for cancelling tensor effects in Faraday spectroscopy, which in turn enabled us to obtain definitive signatures of the spin shot-noise floor in ac magnetometry as described in the Ph.D. thesis of Anthony Miller.

Technology Transfer